International Journal of Natural Resource Ecology and Management
2026, Vol. 11, No. 1, pp. 1–12
https://doi.org/10.11648/j.ijnrem.20261101.11

SciencePG Science Publishing Group

Review Article

Review on Impacts of Soil Salinity and Sodicity on Crop Yield and Management Option

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Abstract

Soil salinity is a major environmental and agronomic challenge that severely constrains crop productivity, particularly in arid and semi-arid regions where evapotranspiration exceeds precipitation. As global food demand increases and irrigated agriculture continues to expand, the extent and severity of salt-affected soils are intensifying worldwide. This review synthesizes the current understanding of the causes, types, and mechanisms of soil salinization, while assessing its physiological and agronomic impacts on major crop species. It highlights how excessive accumulation of soluble salts in the root zone alters soil osmotic potential, inhibits water and nutrient uptake, and disrupts key plant metabolic functions such as photosynthesis and protein synthesis. The resulting physiological stress leads to poor germination, stunted growth, and significant yield reductions. Human-induced factors including inefficient irrigation, poor drainage, deforestation, industrial effluents, and inappropriate fertilizer use are further accelerating secondary salinization. The review also distinguishes between saline, sodic, and saline sodic soils, describing their chemical characteristics, formation mechanisms, and implications for plant growth and soil structure. Furthermore, the responses of both cash crops (cotton, tomato, sugarcane, and sunflower) and subsistence crops (wheat, rice, maize, and sorghum) to varying salinity levels are discussed, highlighting differences in species and varietal tolerance. Finally, the paper underscores the importance of integrated soil and water management practices including leaching, gypsum application, biological reclamation using halophytic grasses, and improved irrigation efficiency to mitigate the impacts of salinity and sodicity. Strengthening farmer awareness, promoting sustainable land management, and adopting innovative technologies for monitoring soil salinity are essential for enhancing agricultural productivity and ensuring food security in affected regions.

Keywords

Crop Yield, Plant Stress, Reclamation, Sodicity, Soil Salinity

1. Introduction

Global water resource scarcity, environmental pollution, and rising soil and water salinization are the hallmarks of the early 21st century. Two risks to agricultural sustainability are the growing human population and the decreasing amount of land accessible for production [4, 55].

It is estimated that by 2025, the global human population

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Received: 10 October 2025; **Accepted:** 25 October 2025; **Published:** 16 January 2026

will reach 8 billion. To prevent or reduce food shortages, it is essential to rehabilitate and properly manage saline soils, as their impact on agriculture must be understood to meet the food demands of a rapidly growing population [33].

Historical and scientific evidence indicates that soil salinity has been expanding since the earliest recorded times and is now recognized as one of the most pressing global challenges, affecting multiple sectors and drawing significant research attention [46]. The first documented case of salt-affected land dates back to around 2400 BC in the Tigris–Euphrates alluvial plains of ancient Iraq [56].

Moreover, before the birth of Christ, the Romans deliberately plowed and spread salt over the fields of conquered Carthage to prevent its people from resettling. Attempts to reclaim and cultivate the area 24 years later were unsuccessful, as the salinized land remained barren and unproductive [30].

At present, salt-affected soils are found across nearly all climatic zones from humid tropical regions to the frigid Polar Regions. These soils occur at various elevations, ranging from areas below sea level, such as around the Dead Sea, to high mountain ranges exceeding 5,000 meters, including the Tibetan Plateau and the Rocky Mountains. Importantly, the presence of saline soils is not confined to desert environments [14, 55].

All soils naturally contain some amount of soluble salts, and all irrigation water sources whether from surface canals or groundwater hold dissolved salts to varying degrees, even when classified as high-quality water [14]. Salinity has been a long-standing issue, especially in arid and semi-arid regions where limited rainfall prevents effective leaching of salts from the root zone [41].

Globally, approximately one-third of agricultural land is affected by salinity, spanning over a hundred countries with diverse climates [68]. According to Mustafa et al. around 955 million hectares of the Earth's surface are impacted by natural (primary) salinity, while 77 million hectares have become saline due to human-induced activities with about 58% of these located in irrigated regions [45]. Munns and Tester further noted that more than 45 million hectares of irrigated land worldwide have been degraded by salt accumulation, and each year, about 1.5 million hectares are removed from agricultural production because of soil salinity [42]. Mustafa also reported that the planet loses roughly ten hectares of arable land every minute, three of which result specifically from salinization in irrigated arid and semi-arid zones [46].

Estimates by Martinez and Clemencia indicate that between 0.25 and 0.50 million hectares of irrigated land are rendered unproductive annually due to salt accumulation in the soil [38]. Similarly, Ghassemi et. al, reported that about 1.2 tons of salt per hectare per year are added through irrigation practices, particularly in dryland regions [27].

The impacts of soil salinization extend beyond environmental degradation and resource depletion; they also impose severe economic costs. For example, [3, 22] estimated that salinization causes global agricultural losses of approximately $11 billion annually due to reduced crop yields, with this figure continuing to rise. Overall, soil salinization is regarded as one of the most significant threats to environmental sustainability and human well-being worldwide, affecting nearly 1 billion hectares equivalent to about 7% of Earth's land area, or roughly twenty times the size of France [40, 55].

Therefore, the objectives of this paper were:

To review/gather information on the causes, types and different definitions of soil salinity.

To review the impacts of salt affected soil on crops yield.

2. Soil Salinity and Its Impacts on Crops Yield

2.1. Different Definitions of Soil Salinity

The definition of soil salinity varies among researchers and disciplines. According to Yadav et. al, it is difficult to define saline soils precisely because the effects of salt injury depend on several factors, including plant species, variety, growth stage, environmental conditions, and the specific types of salts present [55, 78].

Ramoliya and Pandey described saline soils as those containing enough salt in the root zone to restrict crop growth [58]. Similarly, Rhoades and Loveday defined a saline soil as one with an electrical conductivity of the saturation extract (EC_e) equal to or greater than 4 dS m^{-1} [60]. The EC_e value represents the electrical conductivity of the liquid extracted from a soil sample that has been mixed with enough water to form a saturated paste.

Metternicht and Zinck further explained that salt-affected soils are those containing excess salts that impair productivity. They noted that soil salinity affects soil processes through two key mechanisms: the salt concentration in the soil solution (salinity), which influences osmotic potential, and the sodium concentration on the soil's exchange complex (sodicity), which affects soil structure and stability. Over time, salinity can lead to sodicity [40].

A saline soil can also be described as one with a high concentration of soluble salts sufficient to inhibit plant growth. This condition often results from the accumulation of salts commonly dominated by sodium chloride in soil and water, reaching levels that negatively impact agriculture, ecosystems, water resources, and infrastructure [78]. Irrigation salinity, in particular, develops in irrigated landscapes where soluble salts such as sodium chloride, calcium, magnesium, carbonate, bicarbonate, and sulfate accumulate in both soil and water [78].

Salts are composed of positively charged ions (cations) and negatively charged ions (anions). These may dissolve in water (soluble salts) or remain as solid particles in the soil. They originate from various sources, including the soil's parent material, irrigation water, fertilizers, manure, compost, and other amendments. The most common salts that accumulate in soils include calcium, magnesium, sodium, potassium, sulfate, chloride, carbonate, and bicarbonate [17].

A widely accepted definition, cited from FAO 2009, classifies a soil as saline when its electrical conductivity (EC_e) equals or exceeds 4 dS m^{-1}, while soils with EC_e values above 15 dS m^{-1} are considered strongly saline [22]. The major soluble salts typically found in such soils include the cations Na^+ (sodium), Ca^{2+} (calcium), Mg^{2+} (magnesium), and K^+ (potassium), along with the anions Cl^- (chloride), SO_4^{2-} (sulfate), HCO_3^- (bicarbonate), CO_3^{2-} (carbonate), and NO_3^- (nitrate) [66].

2.2. Types, Causes and Factors of Saline Soil

2.2.1. Types of Salinity Based on Their Chemical Properties

Based on their chemical properties and ease of reclamation, salt affected soils are classified in to three groups' namely (a) saline (saline non- sodic), (b) saline sodic (saline alkali) and (c) sodic or alkali (non-saline sodic) soils (Table 1 below). The exchangeable sodium percentage (ESP) used as a classification criterion is computed from exchangeable Na as the percentage of cation exchange capacity (CEC) where concentrations of all constituents are expressed in meq/100g of soil [61].

Table 1. *Summary of Classification of Salt Affected Soils Based on Their Chemical Properties.*

Salt affected soil type	Ece	ESP	pH value
Saline soil	>4	<15	<8.5
Saline sodic soil	>4	>15	<8.5
Sodic (alkali) soil	<4	>15	8.5-10
Non-saline non-sodic	<4	<15	Neutral

Source: Richards, 1954 [61]. (Electrical conductivity of saturation extracts (ECe) at 25 ℃ (dS/m), Saturation (%) of cation exchange capacity with Na (ESP))

According to the U.S. Salinity Laboratory Staff (1954), soil salinity has traditionally been categorized into four levels based on the electrical conductivity (EC) of irrigation water [61]. These categories are:

1) Low salinity: EC less than 0.25 mmhos cm^{-1} (equivalent to 0.25 dS m^{-1})
2) Medium salinity: EC between 0.25 and 0.75 dS m^{-1}
3) High salinity: EC between 0.75 and 2.25 dS m^{-1}
4) Very high salinity: EC greater than 2.25 dS m^{-1}

Furthermore, the FAO Land and Plant Nutrition Management Service (2008), as cited by Yadav et al, provided a more detailed classification of soil salinity based on EC (dS m^{-1}) values and their corresponding effects on crop growth [78]. These classifications are summarized in Table 2, which presents approximate thresholds of salinity levels and their impact on agricultural productivity [64].

Table 2. *Approximate Soil Salinity Classes.*

Salinity Rating	EC (dS m^{-1})	Level of Effect
Slightly saline	1.5–2	Salinity effects usually minimal
Moderately saline	2–6	Yield of salt sensitive plants restricted
Highly saline	6–15	Only salt tolerant plants yield satisfactorily
Extremely saline	>15	Few salt tolerant plants yield satisfactorily

Source: Land, F. A. O, 2008,

2.2.2. Types of Salinity Based on Their Mechanism of Formation

Primary salinity develops naturally over long periods through the gradual accumulation of salts in soils or groundwater. This process occurs due to two main natural mechanisms. The first involves the weathering of parent rock materials that contain soluble salts. As these rocks break down, they release various types of salts primarily sodium, calcium, and magnesium chlorides, and to a lesser extent, sulphates and carbonates with sodium chloride being the most soluble. The second mechanism is the deposition of oceanic salts transported inland by wind and precipitation. These so-called cyclic salts are mainly sodium chloride derived from sea spray and atmospheric processes. Rainwater typically contains between 6 and 50 mg/kg of dissolved salts, with concentrations decreasing farther from the coast. For instance, rain containing 10 mg/kg of salts would deposit approximately 10 kg of salt per hectare for every 100 mm of annual rainfall [54].

Secondary salinization, on the other hand, is induced by human activities that disturb the natural hydrological balance between the water applied to the soil (via irrigation or rainfall) and the water consumed by plants through transpiration. In their natural state, arid and semi-arid ecosystems maintain equilibrium between rainfall and water use by deep-rooted native vegetation, which keeps groundwater tables well below the surface. However, practices such as land clearing and irrigation disrupt this balance. As a result, more water is added to the system than crops can utilize, leading to a rise in groundwater levels and the accumulation of salts near the soil surface [54].

2.2.3. Causes of Soil Salinity

Most saline and sodic soils originate from natural geological, hydrological, and pedological processes. The parent materials that often give rise to these soils include intermediate igneous rocks such as phenolites, basic igneous rocks like basalt, undifferentiated volcanic rocks, sandstones, alluvial, and lagoon deposits [77]. The amount of salt stored in the soil depends on the soil type being lower in sandy soils and higher in clay-rich soils and is inversely related to annual rainfall. For example, in Western Australia, a 40-meter soil profile can contain between 170 and 950 tons of salt per hectare, depending on annual rainfall ranging from 1000 mm to 600 mm [69].

Climatic conditions and water management also influence the rate of salinization. In arid and semi-arid regions, evapotranspiration plays a major role in the formation of saline and sodic soils. Additionally, coastal salinity arises from the intrusion of seawater into rivers and aquifers during flooding events or storm surges [18]. In Asia, for instance, coastal rice fields are often affected by seawater intrusion caused by cyclones in the Indian Ocean. Oceanic or "cyclic" salts, mainly sodium chloride, are carried inland by wind and deposited through rainfall; their concentration depends on wind direction and distance from the coast [64, 69].

Globally, seawater has an almost uniform composition, averaging 55 dS m^{-1} in electrical conductivity, while rainwater typically measures around 0.01 dS m^{-1} [78].

Anthropogenically Induced Salinity: Human-induced salinization primarily occurs due to improper irrigation practices, which disturb the soil's hydrological balance. The use of poor-quality irrigation water without adequate leaching can cause salts to accumulate in the root zone, and it is estimated that nearly 50% of the world's irrigated lands are salt-affected [70].

Despite limited recent assessments of the extent of human-induced salinity, Athar and Ashraf noted that the lack of updated data makes it difficult to predict its impact on future agricultural productivity [4]. Nevertheless, Qiao reported that salinity has been increasing with irrigation expansion since the 1950s, with more than one-third of irrigated land in China's Shansa Province now salinized [57].

Apart from irrigation, several human activities contribute to secondary salinization, including:

Deforestation: The removal of trees disrupts the natural water balance, reduces rainfall, and increases surface temperatures, leading to higher rates of evaporation and salt accumulation [31]. The absence of vegetation cover accelerates soil erosion, increases runoff and sedimentation in rivers, and eventually raises soil salinity levels [19, 31]. For example, in India, deforestation in the Ganges plains and Sundarbans has led to severe soil salinity and alkalinity [70]. Similarly, in Australia, where one-third of soils are sodic and 5% saline [24], clearing of land with shallow groundwater tables containing more than 0.25% soluble salts significantly increases salinization risk [14, 20].

Industrial and Municipal Pollution: Airborne chemicals and waterborne salts from industrial emissions, municipal wastewater, and sludge can accumulate in topsoil, causing salinization and alkalization [10, 69].

Chemical Contamination: Excessive use of fertilizers, pesticides, and chemical amendments in intensive agriculture and greenhouse systems can increase soil salinity [10].

Overgrazing: Common in arid and semi-arid regions, overgrazing reduces vegetation cover, leading to soil exposure, erosion, and the upward movement of salts, sometimes culminating in desertification [70].

2.2.4. Factors Modifying Salinity

The severity of secondary salinity often increases when salts stored in the soil profile or groundwater are mobilized and transported into the root zone. This typically occurs when excess water from irrigation, rainfall, or deforestation raises the water table, particularly in areas already prone to primary salinity [2]. As saline groundwater approaches the surface, evaporation draws salts upward, concentrating them in the root zone [20].

When the water table rises beyond a critical threshold, evaporation and salinization accelerate rapidly, especially under high-temperature conditions. The threshold varies by soil type but is often reached under continuous irrigation. Moreover, inadequate irrigation volumes that fail to leach salts from the root zone exacerbate secondary salinity [60].

Crop response to saline irrigation water depends not only on the salinity level, but also on soil characteristics, irrigation methods, timing, and water application rate, as well as the salt tolerance of crop varieties [74]. The decision to use marginal-quality irrigation water depends on the acceptable level of yield reduction [36].

For surface irrigation systems with a leaching fraction of 0.1 (10% more water than crop evapotranspiration demand):

1) Sensitive crops should receive water with EC $\leq$ 1 dS m^{-1},
2) Moderately sensitive crops: EC $\leq$ 1.8 dS m^{-1},
3) Moderately tolerant crops: EC $\leq$ 3.3 dS m^{-1}, and
4) Tolerant crops: EC $\leq$ 5.8 dS m^{-1}.

Exceeding these thresholds results in yield decline, although higher leaching fractions can slightly raise the tolerance limits depending on field conditions [60].

2.3. Impacts of Soil Salinity on Crops Yield

Salinity is one of the major environmental constraints affecting agricultural productivity, as it negatively influences seed germination, plant vigor, and overall crop yield [42]. Understanding how plants respond to saline conditions is therefore of great practical importance. High concentrations of salts have been shown to inhibit plant growth [39], and excessive salinity levels can eventually lead to plant death [59]. Several studies have documented that elevated salinity delays seed germination and suppresses seedling development [26]. Moreover, different plant organs, tissues, and cells exhibit varying degrees of tolerance to environmental stresses depending on their developmental stage [13, 42, 55].

In most cases, shoot growth is more severely affected by soil salinity than root growth [58], although research on the specific effects of salinity on root development remains limited [25]. In agricultural systems, waterlogging and salt accumulation can significantly impair plant growth and reduce crop productivity, often leading to complete crop failure in severe cases [78].

According to Gupta, salt stress affects plants through both ionic and osmotic mechanisms, with most observed plant responses being linked to these effects [29]. A general manifestation of salinity stress is reduced plant growth [62]. During the onset and progression of salt stress, key physiological processes such as photosynthesis, protein synthesis, and energy and lipid metabolism are disrupted. Initially, plants experience water stress, which restricts leaf expansion and overall development [13, 52].

At low to moderate salinity levels, the primary stress effect is osmotic in nature. Increased salt concentration in the root zone reduces the soil water potential, thereby limiting the water available for plant uptake [42]. As Romero noted, elevated salinity in the root medium decreases leaf water potential, affecting several physiological processes [62]. When soil water potential becomes too low, plants struggle to absorb sufficient water and maintain turgidity [76]. Nonetheless, under moderate salinity, plants can adapt through osmotic adjustment by accumulating compatible solutes to maintain a favorable water potential gradient for water uptake [13, 62].

An excess of salts in the rhizosphere impairs all growth processes of plants such as cell enlargement and division, by damaging growing cells through accumulation of toxic number of ions, reducing photosynthesis and oxidative phosphorylation, depressing specific enzymatic activities, limiting supply of essential metabolites, and, consequently, the synthesis of carbohydrates and even complete distortion of chloroplast in both halophytes and glycophytic. Moreover, stomata of leaf cells of tomato and barley [51].

Yeo et. al observed the short- and long-term effects of salinity was associated with a decrease in leaf K^+ reach to high salinity, lower rates of chlorophyll content per unit leaf proteins and nucleic acids [42, 79].

It was emphasized that fundamental physiological and biochemical processes of cells are unaltered at non-lethal salinities [35]. Specific enzymes, total protein and nucleic acids are reduced quantitatively because the plants remain smaller; however, their specific activities and concentrations remain constant, in balance with a slower growth rate [35].

Prolonged exposure of plants to NaCl induces shrinkage caused plasmolysis and breakage of plasmodesma under NaCl salinity may be located in the growing tissues and not in the mature photosynthetic tissues [43].

Salinity suppressed the enlargement and division of cells in the leaves [9]. This implies that the sensitivity of cell division to salts contributes significantly to the reduction of the leaf area. Salinity level and leaf area are usually inversely related. This could be explained by a water deficit in expanding tissues of rice as explained and ultimately related to reduced photosynthesis. The decrease in photosynthesis may be due to stomata closure or adverse effects of high Na+ and/or Cl^- on photosynthetic reactions [25]. Alternatively, it could be argued that at high external NaCl, a reduced expansion growth in grow on rice and argued that the short-term effects were due to reduced water supply to the growing zone and that the long-term effects were the pathological consequences of continuous excessive ion uptake. Consequently, the rate of utilization of carbohydrates decreased and ultimately there was a reduction in the photosynthetic activity [12].

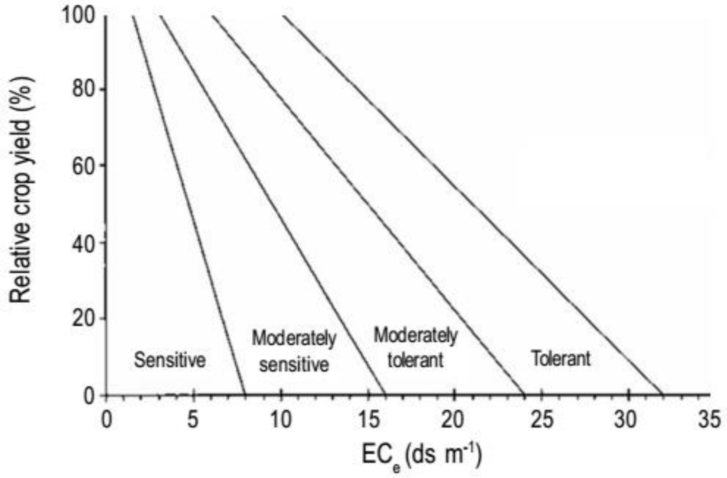

Figure 1. *Crop tolerance to salinity*. Source *[70]*.

Photosynthesis may also be reduced due to reduction in leaf K^+ because of salt stress as reported by Muralitharan in the case of blueberries [13, 44].

Ball *et al*., observed that the change in photosynthesis concentration in rice. After long term exposure photosynthesis may also be caused by a drone area but not per unit weight of plant tissue [7].

Sensitivity of photosynthesis in rice to the average concentration of salt in the leaf was also observed by Yeo et. al [79].

Another primary cause for growth reduction of the whole plant may be the reduced root growth which may lead to reduction in shoot growth. This could be explained by a decreased transport of either mineral nutrients or growth substances from the roots to the shoot [75].

Yeo et. al reported that lack of photosynthesis impairs root function which appears to be independent of salinity perse [79]. Metabolic energy may be the basic limitation to plant growth under salt stress, selective ion uptake is much lower than that conferred by organic molecules synthesized in the cell The ability of a plant to regulate the influx of salts is one of the major factors determining salt tolerance. The most tolerant species have high because the energy is diverted to the processes of selective ion transport, synthesis of organic osmotic and compartmentation [34]; these costs result in diminished growth per unit or substrate (sugar) utilized [13, 36, 45].

Saline soils directly influence crop performance not only by affecting plant physiology but also by altering the soil microbial environment. According to Shabala high concentrations of soluble salts impact soil microorganisms through two main mechanisms: osmotic stress and specific ion toxicity [63]. The presence of excessive soluble salts lowers the soil water potential (making it more negative), which draws water out of microbial and root cells, leading to plasmolysis and potential cell death. Furthermore, a low osmotic potential hampers the ability of both roots and soil microbes to extract sufficient water from the surrounding soil, thereby disrupting essential biological processes and reducing soil fertility [13, 50, 55].

Plants and microbes can adapt to low osmotic potential by accumulating osmolytes; however, synthesis of osmolytes requires large amounts of energy and these results in reduced growth and activity [32].

2.4. Impact of Salinity on Cash Crops

Cash crops are agricultural commodities cultivated primarily for commercial purposes and profit generation, often sold to external buyers rather than used for household consumption [23]. The physiological responses of cash crops to major salinity-related constraints—such as leaf gas exchange, water and ion balance, and osmotic adjustment—were examined in hydroponically grown plants subjected to varying levels of seawater salinity (0%, 25%, 50%, 75%, and 100% SWS) over a six-week period. The results revealed that the salinity threshold for cash crops occurred at approximately 25% SWS, beyond which plant growth was significantly inhibited.

Saline conditions, particularly under NaCl stress, markedly affected gas exchange parameters, including net photosynthesis and water-use efficiency, primarily due to changes in stomatal conductance. Both apparent quantum yield and dark respiration rates declined under increasing salinity, indicating a possible shift toward alternative electron consumption pathways. Furthermore, an elevated carotenoid to chlorophyll ratio and higher leaf area ratio (LAR) were observed, which collectively reduced electron flow through the photosystems thereby decreasing photosynthetic efficiency and mitigating the risk of photoinhibition [13].

Leaf water and osmotic potentials declined following exposure to salinity stress, with sodium (Na^+) and chloride (Cl^-) ions being the main contributors to the observed osmotic adjustments in both juvenile and mature leaves. In addition, the concentrations of essential nutrients such as calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), and nitrate temporarily decreased under salt stress. This transient decline appeared to be more closely linked to plant growth dynamics rather than ionic imbalance, as the lowest nutrient levels coincided with the period of maximum yield [13, 49].

2.4.1. Cotton

In most crop species, increasing salinity levels are typically associated with reduced vegetative growth and a corresponding decline in fruit yield. However, some exceptions have been noted in cotton. For instance, Bernstein and Hayward observed a significant reduction in the vegetative growth and vigor of cotton plants under elevated salinity, yet seed cotton yield remained largely unaffected [7]. Similarly, Ehlig reported that salinity reduced plant height, the number of main stem nodes, and internode length in cotton, but did not consistently decrease flower production [16, 19, 21].

These reductions in vegetative growth without an immediate impact on reproductive output likely occurred at salinity levels below the yield threshold reported by Ayers and Westcot and Maas and Hoffman, which is 7.7 mmhos/cm (ECe) for cotton [5, 35]. Nonetheless, the salinity threshold for yield reduction is not fixed and may vary due to several factors. For example, Thomas documented yield declines at lower ECe levels of 3–5 mmhos/cm, a discrepancy that may be attributed to differences in experimental conditions [35, 72] and variations in the salt tolerance of the plant materials used [16, 21, 36].

Environmental factors such as temperature, humidity, and the chemical composition of the soil solution can further influence the specific salinity levels at which yield reductions occur [15, 37, 48]. Generally, declines in fruit yield under salinity stress are attributed to decreases in both fruit size and number [8]. Moreover, because salinity often suppresses vegetative growth, it may delay flowering in many crops. However, in indeterminate fruiting species like cotton, reduced vegetative growth can sometimes lead to earlier crop maturity, thereby advancing the final harvest [8, 13, 16, 21, 55].

2.4.2. Avocado

Avocado trees are highly sensitive to saline conditions, with notable variation among different races the Mexican race being the most salt-sensitive, while the West Indian race exhibits the highest tolerance. Although avocado roots can restrict sodium uptake to some extent, chloride ions readily move with the transpiration stream, leading to leaf tip burn and eventual leaf abscission [23].

2.4.3. Sunflower

Sunflower exhibits moderate tolerance to salinity, with little to no adverse effects observed at soil salinity levels up to 4.8 dS/m. The crop is widely cultivated in arid and semi-arid regions where salinity often poses a significant challenge. However, with proper irrigation management and effective leaching practices, sunflower can be successfully grown on salt-affected soils. Regular leaching is crucial to prevent the accumulation of salts in the root zone, thereby safeguarding both seed and oil yields under saline conditions. The use of moderately saline water for irrigation is feasible, provided that adequate soil moisture is maintained consistently and salinity buildup is minimized through leaching [23, 64].

2.4.4. Sugarcane

Sugarcane is considered moderately sensitive to salinity and particularly vulnerable to sodicity [46]. Elevated salinity levels can induce water stress in plants, leading to symptoms such as leaf scorching, wilting, and stunted growth. When soil salinity, expressed as the electrical conductivity of a saturated paste extract, remains below 20 dS/m, little to no adverse effect on crop performance is observed. However, cane yield begins to decline noticeably at salinity levels between 30 and 40 dS/m, with 40 dS/m generally regarded as the upper threshold for economically viable production [13, 63].

2.4.5. Potato

The crop exhibits moderate sensitivity to soil salinity, with a threshold electrical conductivity of the saturated soil paste extract (ECe) ranging between 2 and 3 dS/m, beyond which yield progressively declines, reaching complete (100%) yield loss at approximately 10 dS/m.

2.4.6. Tomato

The crop is moderately sensitive to salinity, with an average root zone salinity threshold (ECe) of approximately 2.5 dS/m. Yield declines progressively as salinity increases, reaching about 50% reduction at an ECe of 8 dS/m and complete yield loss at 13 dS/m in some studies. For practical irrigation purposes, the long-term water salinity threshold varies with soil type: around 3.5 dS/m for sandy soils, 2.0 dS/m for loamy soils, and 1.2 dS/m for clay soils [6]. Interestingly, mild salinity stress during fruit ripening can enhance fruit quality without negatively affecting yield. Indeed, moderate salinity has been shown to improve fruit quality, although often at the expense of reduced total yield, as demonstrated in several studies conducted in Israel [13].

2.4.7. Rice

Rice is classified as a salt sensitive crop [65]. In South Asia, approximately 9–12 million hectares of lowland rice are affected by salinity and/or alkalinity, resulting from either seawater intrusion in coastal regions or salinization of inland soils and irrigation water [11]. The threshold for yield reduction is around 3 dS/m soil electrical conductivity (ECe), with nearly 90% yield loss occurring at 10 dS/m ECe. Rice shows relatively higher salt tolerance during germination, tillering, and near maturity, but is highly sensitive during the early seedling stage, flowering, and grain-filling periods [36].

2.4.8. Soybean

Soybean is generally considered a salt-sensitive crop, although considerable variation in salt tolerance exists among cultivars. Certain moderately tolerant varieties are able to limit chloride accumulation in their leaves through exclusion mechanisms. However, a high phosphate concentration in the growth medium has been found to enhance sodium uptake, thereby decreasing the salt tolerance of some cultivars [27, 36].

2.5. Impact of Salinity on Subsistence Crops

Subsistence crops are cultivated primarily to meet the food and livelihood needs of the farmer's household, with little or no surplus for trade. A typical subsistence farm includes a variety of crops and livestock necessary to feed and clothe the family throughout the year [73]. High concentrations of salts in the soil primarily affect these crops through the soil solution, with dry soils generally having a greater negative impact than wet soils. Salinity can inhibit plant growth through two main mechanisms. First, the osmotic or water-deficit effect occurs when salts in the soil solution reduce the plant's ability to take up water, leading to slower growth. Second, the salt-specific or ion-excess effect arises when excessive salts are transported to the leaves via the transpiration stream, causing cellular injury and further reductions in growth [28].

2.5.1. Wheat

Wheat is generally regarded as moderately tolerant to soil salinity. In sand or solution culture studies, shoot growth declines roughly linearly with increasing sodium concentration, with 100 mM sodium (approximately 10 dS/m) reducing shoot growth by about 45% in bread wheat and 50% in durum wheat. By comparison, barley exhibits a reduction of around 40%, while rice experiences a more severe reduction of approximately 75%. New wheat cultivars with enhanced salt tolerance are increasingly being developed [23, 36].

2.5.2. Maize

This crop is considered to have medium sensitivity to salinity [6]. Its responses to salt stress are similar to those observed under water stress, including reduced leaf expansion, decreased stomatal conductance and photosynthesis, and accelerated leaf and canopy senescence. The relative sensitivity of these physiological parameters under salinity mirrors their responses to water deficit [13, 23].

2.5.3. Barley

Salinity is a significant stress factor affecting barley production in certain irrigated areas; however, barley is generally regarded as the most salt-tolerant of the major cereal crops. Soil fertilization requirements for barley should be determined based on expected yield, soil type, and inherent soil fertility. As a general guideline, for every ton of grain produced per hectare, barley requires approximately 30 kg of nitrogen (N), 5 kg of phosphorus (P), and 20 kg of potassium (K). Actual nutrient uptake depends on both the availability of native and applied fertilizers and the crop's uptake efficiency, which typically does not exceed 60%. Nitrogen status in the crop influences not only total yield but also grain protein content, with lower protein levels preferred for malting purposes and higher protein content better suited for animal feed [13, 23].

2.5.4. Sorghum

Sorghum is moderately tolerant to salinity. As soil electrical conductivity (EC) increases from 11 to 18 dS/m, grain yield declines from 50% to complete (100%) loss. Many of the temperature effects on sorghum have been discussed under growth and development. Leaf extension closely follows air temperature up to approximately 34 ℃. Pollination and fruit set may fail if night temperatures drop below 12–15 ℃ during flowering, and pollen produced below 10 ℃ or above 40 ℃ is likely non-viable. Sorghum grain contains roughly 1.5% nitrogen (N) and 0.25% phosphorus (P). For a target yield of 8 tons per hectare, the grain alone removes 120 kg of N and 20 kg of P. Fertilization strategies must also account for nutrients in the stover, as well as the efficiency of applied fertilizers and native soil supply. In water-limited environments, fertilization rates should be reduced accordingly. In regions prone to terminal drought, excessive early-season N application should be avoided, as rapid early growth can deplete soil moisture and exacerbate drought stress later in the season [23, 13, 55].

2.5.5. Alfalfa

Alfalfa exhibits tolerance to relatively high salinity in the lower root zone, provided that the upper soil layers remain free of salts. The crop is more sensitive to sodium (Na^+) than chloride (Cl^-), with sodium accumulation being the primary factor contributing to yield reductions when irrigated with saline water. Even moderate salinity in irrigation water can lead to the downward movement of salts, allowing roots to grow in deeper zones with lower salinity. Significant yield losses are expected when soil salinity exceeds 10 dS/m; however, under such conditions, the absolute yield of alfalfa can still surpass that of many so-called "salt-tolerant" grasses [23, 53].

Yield potential of selected crops as influenced by soil salinity (ECe) (Ayers and Westcot, 1985) [6].

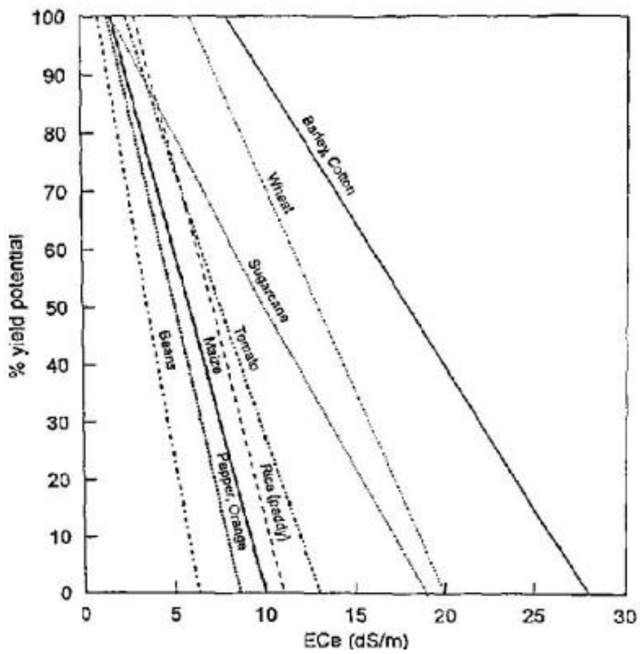

Figure 2. *Yield potential of selected crops as influenced by soil salinity (ECe) [6].*

3. Reclamation Measurement

3.1. Reclamation of Saline Soils

Saline soils are characterized by high soluble salt concentrations (EC > 4 dS m^{-1}) but typically have good structure and permeability. The main objective in managing saline soils is to remove excess salts from the root zone through effective leaching with high-quality water. Methods such as continuous ponding, intermittent ponding, and sprinkler irrigation can be used depending on soil texture and water availability [14, 29, 71]. Continuous ponding applies large volumes of standing water to flush salts downward, while intermittent ponding and sprinkling use smaller, repeated applications that save up to two-thirds of the water. Adequate drainage systems, including subsurface tile drains, are essential to prevent salt re-accumulation [71, 74]. Cucci et al. reported that leaching combined with gypsum application decreased soil electrical conductivity (ECe) from 12.34 to 3.66 dS m^{-1}, corresponding to a 70.5% reduction in salinity [4, 29]. These results confirm that proper leaching and drainage, supported by amendments to maintain soil structure, are vital for successful saline soil reclamation [17, 27, 33, 67].

3.2. Reclamation of Sodic Soils

Sodic soils have low salinity (EC < 4 dS m^{-1}) but a high exchangeable sodium percentage (ESP > 15%) and elevated pH (> 8.5). Excess sodium causes clay dispersion, surface sealing, and poor water infiltration, making these soils physically degraded and less productive [24, 47, 61]. Reclamation focuses on replacing exchangeable sodium (Na^+) with calcium (Ca^{2+}) and subsequently leaching the displaced sodium salts out of the root zone. Gypsum ($CaSO_4\ 2H_2O$) is the most effective and economical chemical amendment [5, 6, 29, 61], while elemental sulfur or sulfuric acid can be applied in lime-rich soils to release calcium from native carbonates [27, 34]. The gypsum requirement depends on the soil's cation exchange capacity (CEC), depth to be reclaimed, and target ESP; typically, 3–5 tons of pure gypsum per acre are applied in stages [61, 71]. Applying gypsum incrementally each year and monitoring ESP reduction ensures gradual reclamation as calcium percolates through the soil profile [29, 47]. To enhance structural stability, the addition of organic matter (e.g., compost or manure) and salt-tolerant cover crops is encouraged, as these improve aggregation, infiltration, and biological activity [26, 52, 78]. Overall, chemical amendment combined with proper leaching and drainage effectively reduces sodicity and improves the productivity of sodic soils [17, 24, 74].

3.3. Reclamation of Saline-sodic Soils

Saline sodic soils exhibit both high salinity (EC > 4 dS m^{-1}) and high sodicity (ESP > 15%) and therefore require an integrated reclamation approach to manage both excess salts and exchangeable sodium [17, 27, 29, 61]. The presence of soluble salts temporarily maintains soil flocculation, but once leaching begins, dispersion can occur if calcium is not supplied. Thus, reclamation should begin with gypsum application to replace Na^+ with Ca^{2+}, followed by controlled leaching using good-quality, low-sodium water [5, 6, 71]. Cucci et al. reported that gypsum combined with leaching water reduced ESP by 50.9% in Bologna soil and 41.4% in Locorotondo soil, while also increasing permeability and hydraulic conductivity [4, 29]. In a related study in Ethiopia, Abate et al. demonstrated that integrating gypsum (125% requirement, ≈ 2.5 t ha^{-1}) with halophytic grasses such as Rhodes grass (*Chloris gayana*) and Panicum grass (*Cynodon dactylon*) achieved superior results—reducing SAR by 70–80%, ESP by 85%, and improving infiltration rates from 1.22 cm h^{-1} to 6.3 cm h^{-1} [1]. The grasses enhanced reclamation by absorbing and secreting excess salts and adding organic matter to the soil. This integrated chemical–biological method proved more efficient than using gypsum or vegetation alone. Continuous monitoring of EC, SAR, and ESP, along with adequate drainage, is essential to ensure progressive improvement [29, 67, 71]. Therefore, the combined use of gypsum, leaching, and salt-tolerant vegetation is considered the most effective and sustainable management strategy for saline sodic soil reclamation [1, 4, 29, 33, 64, 71].

Soil salinity is increasingly recognized by scholars as a major challenge to sustainable agricultural development. Numerous studies have revealed that the extent and severity of this problem are rapidly increasing. Salinity negatively impacts plant growth and water quality, leading to reduced crop yields and agricultural productivity. As salinity levels rise, plants struggle to absorb water from the soil. Moreover, high salinity disrupts the balance of essential plant nutrients and may even introduce toxic elements harmful to plant health. It also alters the physical and chemical properties of soil, causing issues such as surface compaction and erosion.

Excessive salt concentrations can dehydrate beneficial soil microorganisms' bacteria and fungi reducing microbial activity essential for organic matter formation and nutrient cycling. This degradation of soil structure, coupled with the loss of vegetation cover, leads to increased vulnerability to erosion, including sheet, rill, gully, and wind erosion often intensified by salinity.

One of the primary causes of soil salinity and sodicity is inadequate drainage. Improper or absent drainage systems exacerbate environmental degradation. In the research area, the drainage system was gradually introduced only after the construction of the irrigation network, which was a critical oversight. Drainage infrastructure should be planned and implemented simultaneously with irrigation systems. Salinity tends to increase between irrigation intervals due to evapotranspiration, a factor often overlooked by conventional salinity charts [55].

In general, the presence of soluble salts in soils, groundwater, and surface water bodies is a significant contributor to land degradation and environmental challenges worldwide. The economic and ecological consequences of salinity are considerable, including reduced agricultural productivity, diminished water quality for domestic, agricultural, and industrial use, damage to infrastructure, and loss of biodiversity in both terrestrial and aquatic ecosystems. Therefore, it is crucial to implement effective management strategies for salinity-affected soils.

Abbreviations

CEC	Cation Exchangeable Capacity
Dsm	Desicemeter
ECs	Electrical Conductivity of the Saturation Extract
ESP	Exchangeable Sodium Percentages
ET_o	Evapotranspiration

FAO	Food and Agriculture Organization
LF	Leaching Fraction
PET	Potential Evapotranspiration
PPM	Parts per Million
SAR	Sodium Adsorption Ratio
Sws	Seawater Salinity
WMO	World Meteorological Organization

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Conflicts of Interest

The authors declare no conflicts of interest.

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